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Army Modeling and Simulation Standards for Dynamic Atmospheric Environments: CLIMAT, COMBIC, XSCALE

Richard C. Shirkey
Information Science and Technology Directorate
Battlefield Environment Division

ARL-TR-1834 **July 1999**

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In concert with DoD objectives, the Army Modeling and Simulation Office (AMSO) has introduced a process to develop standards in 19 separate categories relevant to Army Modeling and Simulation. This process is explained and the AMSO standards category of Dynamic Atmospheric Environments is defined and examined. Approved models in this category are presented in a fashion that allows the potential user to ascertain whether they are applicable for a given simulation. These models currently consist of the climatology model (CLIMAT), the smoke and dust transport and diffusion model Combined Obscuration Methodology for Battlefield Induced Contaminants (COMBIC), and the natural aerosol transmission model Scaled Extinction model (XSCALE).

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Preface

This document provides a summation of how the Army's standards development process works. Also included in this report is abridged documentation for the approved standards in the standards category of Dynamic Atmospheric Environments. By using this document the reader can ascertain how to influence the Army's standards development process and to determine whether the Dynamic Atmospheric Environments standards climatology model (CLIMAT), Combined Obscuration Model for Battlefield Induced Contaminants (COMBIC), Scaled Extinction Model (XSCALE) apply to their work.

The development of models and algorithms for use in simulations is a time consuming and costly process. To avoid duplication and concurrently establish standards for U.S. Army modeling and simulation, the U.S. Army Modeling and Simulation Office has established 19 standards categories to support the six modeling and simulation objectives articulated in the U.S. Department of Defense (DoD) Modeling and Simulation Master Plan.

The U.S. Army Modeling and Simulation Office's standard category of Dynamic Atmospheric Environments (DAE) currently has three approved standards: climatology model (CLIMAT), Combined Obscuration Model for Battlefield Induced Contaminants (COMBIC), and XSCALE.

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Overview

Weather has always played a decisive role in warfare. Literature, movies, and historical accounts of battles depict the struggles of the infantryman trudging through the sloppy mud of the jungle, the snowy cold of the north, or the searing heat of the desert. Under inclement weather conditions, the eventual winner of the battle was almost always the individual or battle group who could better withstand the elements of weather and turn those elements to their benefit.

One of the U.S. Department of Defense (DoD) Modeling and Simulation Master Plan's six objectives is to provide timely and authoritative representations of the natural environment. In order to support the six DoD objectives, the U.S. Army Modeling and Simulation Master Plan introduced and defined the standards development process and established the role of standards category coordinators within the U.S. Army. To keep the Army community abreast of changes, the coordinators of these standard categories annually provide the U.S. Army Modeling and Simulation Office (AMSO) a report in their area on the status of standardization, significant progress during the past year, and standardization priorities for the following year. One of these 19 standard categories is the Dynamic Atmospheric Environments (DAE). The DAE category should not be confused with the Dynamic Terrain category.

In today's climate of reduced funding and decreasing budgets, it is imperative that models are reused and standards developed. This is particularly true in the DAE area since simulation of military operations must include realistic representations of the natural environment. However, a simulation attempting to emulate the real world around us is only as good as the computer models it uses. To correctly model atmospheric effects is a formidable task. Atmospheric effects range from microscale effects, such as the movement of smoke plumes and terrain-induced turbulence, to large-scale synoptic effects caused by adverse weather patterns. These effects must be included in models from detailed simulations that require physics-based models to high-level aggregated simulations that require only a "broad brush" outlook and do not require the computational burden of detailed models. This report describes the U.S. Army's procedure for establishing and promulgating standards for the advancement of M&S in

the area of DAE and the atmospheric climatology (CLIMAT), Combined Obscuration Methodology for Battlefield Induced Contaminants (COMBIC), and Scaled Extinction (XSCALE) models that have been approved as standards in this area.

Background

In 1994, AMSO published the U.S. Army's first M&S Master Plan. This document described the U.S. Army M&S Environment encompassing the principles of interoperability, credibility, commonality, and reuse. The Master Plan also articulated the concept of developing M&S technical standards through a bottom-up approach with decentralized authority. The plan introduced and defined the standards development process and established the role of standards category coordinators. This created a new way of thinking about standards development; it provided a framework for M&S technical standards to be developed by those closest to the problem. The U.S. Army's 19 standards categories, one of which is DAE, cover the realm of technologies and processes important to M&S development and use within the U.S. Army. With the publication of DoD Directive 5000.59-P, M&S Master Plan, the U.S. Army expanded its desired endstate to encompass DoD's M&S objectives. In the 1997 U.S. Army M&S Master Plan, an objective was added that specified the U.S. Army's goal of developing "a comprehensive set of standards that facilitates efficient development and use of M&S capabilities," and the standards development process was further refined to include a more formal procedure to nominate and approve M&S standards.

In order to achieve this process, AMSO has developed internet online web-based tools: the Standards Nomination and Approval Process (SNAP) and the U.S. Army Standard Repository System. In addition to these tools, on-line reflectors and various conferences and workshops are available for interaction and discussion leading to implementation of standards. Criteria for becoming a standard is defined within each of the standards categories; common sense also dictates that a proposed standard should be based on a mature model that is in widespread use. Many models contained in the Electro-Optical Systems Atmospheric Effects Library (EOSAEL) meet this criteria. Specifically, the climatology model CLIMAT, the smoke diffusion model COMBIC, and the aerosol extinction model XSCALE. These three models have been approved as standards for U.S. Army-wide M&S usage in the standards category of DAE.

Conclusions

The CLIMAT, COMBIC and XSCALE models have been in existence since the inception of EOSAEL in 1979. These models have proven their usefulness and validity through usage in stand-alone modes and also via incorporation into various other models and simulations. They have undergone validation and verification through comparison with real-world tests and other similar models. Therefore, through this widespread usage, and the requirement of the U.S. Army to have developed standards, these models have been approved as standards in AMSO's DAE category.

Recommendations

As approved standards it is recommended that the three atmospheric models CLIMAT, COMBIC, and XSCALE, described herein, be utilized throughout the U.S. Army's atmospheric M&S community.

1. Introduction

1.1 The DoD Model and Simulation Master Plan

The Department of Defense (DoD) publishes and maintains the DoD Modeling and Simulation (M&S) Master Plan to direct, organize, and concentrate the Department's model and simulation capabilities on resolving commonly shared problems. [1] It focuses on management and a model and simulation technical support strategy to facilitate interoperability and reuse. Simultaneously, it provides flexibility for DoD components to exercise their authority and judgment in executing their unique model and simulation management responsibilities.

1.1.1 The DoD Vision

In order to understand the U.S. Army's standards process, we must first examine DoD's vision for M&S. The October 1995 DoD M&S Master Plan establishes a vision to help focus DoD's M&S community on core functions and to apply M&S in ways that would enhance overall U.S. military capability. This vision is that "Defense M&S will provide readily available, operationally valid environments for use by the DoD components:

- to train jointly, develop doctrine and tactics, formulate operational plans, and assess warfighting situations; and
- to support technology assessment, system upgrade, prototype and full-scale development, and force structuring.

Furthermore, common use of these environments will promote a closer interaction between the operations and acquisition communities in carrying out their respective responsibilities. To allow maximum utility and flexibility, these M&S environments will be constructed from affordable, reusable components interoperating through an open systems architecture."

The Vision runs the gamut from high-fidelity engineering models to highly aggregated, campaign-level simulations. These models and simulations include differing levels of spatial and temporal resolution, differing degrees of physical realism, and varied computational techniques. They also

integrate a mix of virtual, constructive and live computer simulations, connecting models, warfighting systems and weapon system simulators.

1.1.2 DoD Objectives

Through this Vision, six DoD-wide objectives were derived. These objectives address those aspects of M&S that are common and which will ensure interoperability where appropriate. Figure 1 shows these six objectives and the breakout of the objectives into sub-objectives.

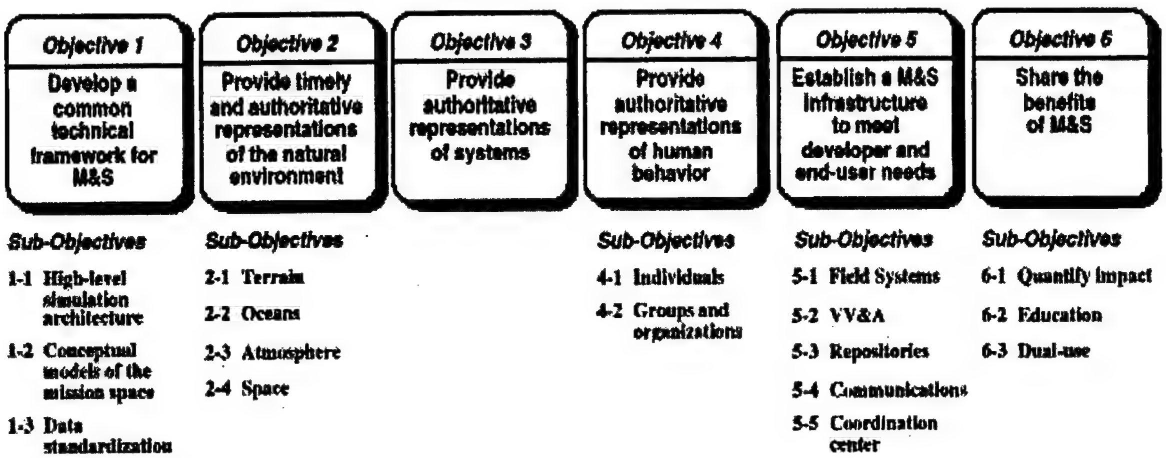

Figure 1. DoD M&S objectives and sub-objectives.

The second DoD objective, to "Provide timely and authoritative representations of the natural environment" has representation of the atmosphere as one of its sub-objectives (2-3). These atmospheric representations are developed in a zone from the earth's surface to the upper boundary of the troposphere and include:

- particulate and aerosol data on haze, dust, and smoke contaminants (to include nuclear, biological, and chemical effects);
- data on atmospheric pressure, temperature, humidity, wind speed and direction, visibility, obscurants, fog, cloud height and amount, illumination, radiative energy, and severe weather; and
- process models for generating, moving, dispersing, and dissipating atmospheric phenomena in four-dimensional (i.e., three-dimensional spatial location over time) representations of both natural and modified environments (to include conventional, nuclear, chemical, biological, and other weapons and/or collateral effects).

1.2 The U.S. Army Model and Simulation Master Plan

The Department of the Army publishes and maintains the U.S. Army Model and Simulation Master Plan, which embraces the objectives of the DoD M&S Master Plan, establishes the U.S. Army's M&S objectives and management processes, and promotes standardization within each objective area. [2] The plan applies to all U.S. Army agencies engaged in development and employment of M&S and establishes the U.S. Army's strategic vision to guide M&S investments. The Department of the Army also publishes the U.S. Army Model and Simulation Standards Report. [3] Published annually, this document provides a snapshot of Army M&S standards efforts as work progresses toward the objective environment.

The U.S. Army's M&S Master Plan articulates the objective U.S. Army M&S environment, introduces and defines the standards development process, and establishes the role of standards category coordinators. The 19 standards categories were established by the U.S. Army Modeling and Simulation Office (AMSO) to support the six DoD M&S objectives. Through the development of standards, the U.S. Army M&S community shares techniques, procedures, processes, and applications. M&S builds on the work of others and advances M&S in step with technological advances. Each of the 19 categories are guided by the AMSO established standards development process — an iterative and consensus based process (figure 2).

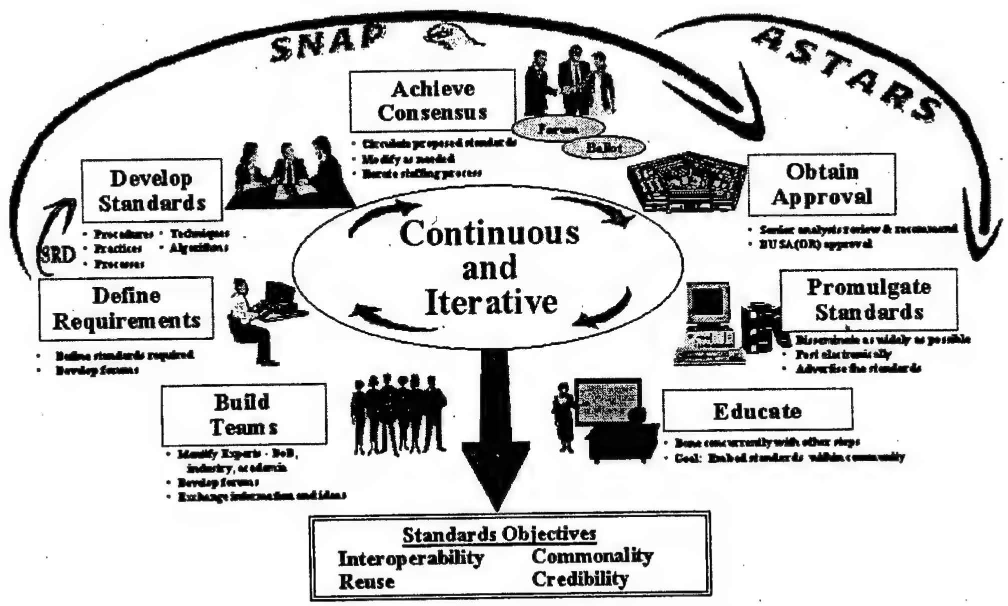

Figure 2. U.S. Army standards development process.

2. U.S. Army Standards

2.1 Definitions

The term standard is applied in the broadest context to include procedures, practices, processes, techniques, data, and algorithms. Standards for M&S cover a variety of topics and the type and source of relevant standards varies with each standards category. Standards are developed within the U.S. Army M&S community and are also adopted from other disciplines and organizations. These standards build technical M&S algorithms, heuristics, procedures, and other appropriate M&S standard methods, to support commonality, reuse, sharing, and interoperability.

2.2 Levels of Standards

There are three levels of standards. The different levels indicate the degree of maturity of the standard and the level of enforcement. The goal is to develop standards that have value-added to the consumer.

1. *Draft Standards*. Draft standards are the initial level standards. These standards have not completed the review process. They are available to the community for use as best meets their program goals pending further maturation to a higher level.

2. *Approved Standards*. Deputy Under Secretary of the Army (Operations Research) [DUSA (OR)] approved standards are the next higher-level. These standards have been reviewed and demonstrated sufficient maturity and consensus to warrant their recommendation to the DUSA (OR) for approval. The intent is to designate standards that facilitate interoperability, reuse, and efficiency that developers can adopt to reduce their development, verification, validation and accreditation, and operational costs.

3. *Mandatory Standards*. Mandatory Standards are the highest-level standards and are promulgated by regulation or policy statement. Developers and users of U.S. Army M&S systems must follow these standards.

2.3 Standards Approval Process

The AMSO Standards Nomination and Approval Process (SNAP) (http://www.msrr.army.mil/snap) is a web-based tool used to track, discuss, and vote on standards nominations from the M&S Community. Any individual may identify a new M&S standard requirement by submitting a Standards Requirements Document (SRD) for consideration. Candidate SRDs are discussed on internet-based reflectors established for each of the M&S standards categories to facilitate widespread review and comment and, when appropriate, fleshed-out by the standards category into draft standards. Once consensus within a standards category is reached on a draft standard, it is reviewed by senior subject matter experts who recommend approval or disapproval through the online voting system in SNAP. Final authority rests with the DUSA (OR). If approved by the DUSA (OR), the suggestion is adopted and integrated as a new U.S. Army M&S standard into the U.S. Army Standards Repository System (ASTARS) (http://www.msrr.army.mil/astars). ASTARS is a web-based electronic standards storage application that allows users to store U.S. Army M&S standards and supporting documents and applications in a central, secure location; ASTARS can be considered the library for SNAP.

Because the standards approval process is iterative and consensus-based, tools that have been developed for this use are varied. They include such repositories as the Army node of the M&S Resource Repository (http://www.msrr.army.mil), a collection of M&S resources, and SNAP using ASTARS, applications discussed previously. Model improvements leading to standards are also made through yearly proposals under the U.S. Army Modeling Improvement Program (AMIP) or Simulation Technology (SIMTECH) program. Two important forums for discussion and dissemination of ideas are annual the Tri-Service Battlespace Atmospheric and Cloud Impacts on Military Operations conference (http://www.hrs.afrl.af.mil/bacimo98/); and the semi-annual Simulation Interoperability Workshop (http://www.sisostds.org/siw/), sponsored by the Simulation Interoperability Standards Organization. Finally, the Dynamic Atmospheric Environment (DAE) reflector (AMSO-SCC-DYNENV@sc.ist.ucf.edu), homepage (http://www.amso.army.mil/sp-div/dyn-env.htm) and the annual AMSO-sponsored U.S. Army M&S Standards Workshop, where the 19 standards categories meet for discussion and work within/between categories, are additional forums for discussion. During this workshop, AMIP nominations, definitions, requirements, objectives and roadmaps are reviewed and updated for the various

categories as necessary. Roadmaps allow easy visualization of areas that are in need of improvement or that are omitted in their entirety; they also indicate where improvements in existing models need to be made and/or their degree of maturation. All of these areas are crucial to the standards development process as outlined in figure 2.

3. Dynamic Atmospheric Environments

3.1 Definition

The Dynamic Atmospheric Environments (DAE) category is focused on weather effects and how weather impacts the battlefield. The battlefield environment includes many sources of aerosols and particulates such as chemical/biological agents, smoke, dust, and chaff. These add to the natural environment increasing the presence of nonuniform aerosol regions. Weather, atmospheric transport and diffusion processes, and the attenuating effects of the environment on the propagation of electromagnetic energy all impact target acquisition and high technology weapons. The atmosphere and clouds provide cues, alter target and background signatures, and produce scene clutter both in the real world and in realistic computer-generated simulations. All these weather effects and impacts are in the DAE domain and are in harmony with the DoD objective representation of the atmosphere.

Consideration of the above leads us to the definition of the DAE category for M&S:

> "*those objects, algorithms, data and techniques required to replicate weather, weather effects and impacts, backgrounds, acoustics, and transport and diffusion of aerosols and battle by-products.*"

Note that the DAE category does not explicitly cover terrain, but it influences terrain insofar as weather effects are concerned. For example, snow cover will change the surface albedo, the amount of rainfall will change the condition of the ground state, thereby changing mobility; other examples may be found. Since target acquisition depends heavily on target and background signature propagation through the atmosphere and on diurnal heating effects, background signatures fall under the purview of DAE. Target signatures per se, however, are in the domain of the standards category of Acquire.

3.2 Requirements

The natural environment is important in determining the outcome of real battles. Included in this area are weather features (clouds, fronts, and thunderstorms, etc.) and weather effects such as target contrast changes.

However, "playing" weather in simulations is currently in its infancy. Meteorological data and weather scenarios are becoming available through efforts such as the Defense Modeling and Simulation Office's funded Environmental Scenario Generator, [4] the Master Environmental Library (MEL), [5] and the Total Atmosphere and Ocean Server. [6] But converting these meteorological parameters and weather representations into quantitative effects that are not computationally burdening for simulations is a difficult proposition.

Due to the dynamic range of atmospheric processes, the DAE category must represent a requirement spectrum ranging from small-scale effects, necessary to correctly visualize scenes, to large-scale effects, to correctly represent weather impacts. On the small-scale end physics-based calculations such as the U.S. Army Research Laboratory's (ARL) Weather and Visualization Effects for Simulations (WAVES), [7] are needed to represent high-fidelity natural and battlefield-induced atmospheric effects (e.g., smoke, illumination, rain/fog, transport and diffusion, etc.) but usually are available only at a high cost in processing time.

To reduce this burden a scenario-specific natural environmental representation can be precomputed or prescripted (if time-varying) for later real time simulations. However, embedded environmental processes include battlefield-generated clouds from munitions, vehicles, agents, and fires whose location and time of introduction cannot be completely prescripted. They are event-driven, resulting from battle actions and combatant decisions and thus can only partly be precomputed. These processes are embedded in the natural aerosol environment and are generally more localized and dynamic than other battlefield effects. Atmospheric parameters and effects from embedded processes are thus both superimposed on and affected by input conditions described by the natural environment representation. In some cases, the environmental-embedded processes will be the dominant factors in determining the outcome of a simulation.

While progress has been made in this area in recent years, notably in the Defense Advanced Research Projects Agency's Synthetic Theater of War – Synthetic Environments (STOW-SE) program, such efforts require dedicated hardware and precomputed weather effects scenarios. The underlying models in these simulations are inherently computationally intensive. Engineering level line-of-sight propagation models from ARL's Electro-Optical Systems Atmospheric Effects Library (EOSAEL) [8] and

the Air Force Research Laboratory's Moderate Resolution Transmission (MODTRAN), [9] while fast, are still burdensome considering the wargaming playbox, the potential number of lines-of-sight between entities, and the number of pixels needed to generate virtual scenes.

At the other end of the spectrum are the high level simulations that deal with aggregated units. These simulations simply cannot afford to include detailed calculations for individual platforms and systems. Thus, a new approach to include weather at a realistic level of fidelity and still maintain "faster than real time" simulation capability is being investigated [10] using ARL's rule-based Integrated Weather Effects Decision Aid (IWEDA) [11] model. This model, based in U.S. Army doctrine, provides color-coded matrix charts showing the impact weather has on various platforms, sensors and weapons systems thereby allowing for simple and fast assessments over large areas without a heavy computational burden.

Therefore, in order to provide for the disparate needs of both detailed and aggregate simulations, DAE requirements, presented in table 1, are general in nature.

Table 1. Dynamic atmospheric environments requirements

Provide fundamental environmental models for M&S
Provide methodologies for determining consistent data sets for environmental effects models
Provide standardized data bases for system performance analysis
Identify requirements for standard atmospheric scenarios

3.3 Objectives

In concert with these requirements, the DAE category has the objectives of identifying fundamental gaps, ingesting live meteorological data and real time forecasts into simulations along with development of: fundamental dynamic environment data bases to support modeling and simulation, standard synthetic natural environment scenarios and backgrounds, and standard tools to facilitate system performance analyses and weather impact decision aids. Models that currently exist or are under development that will satisfy these objectives are embodied in the DAE category roadmap (figure 3).

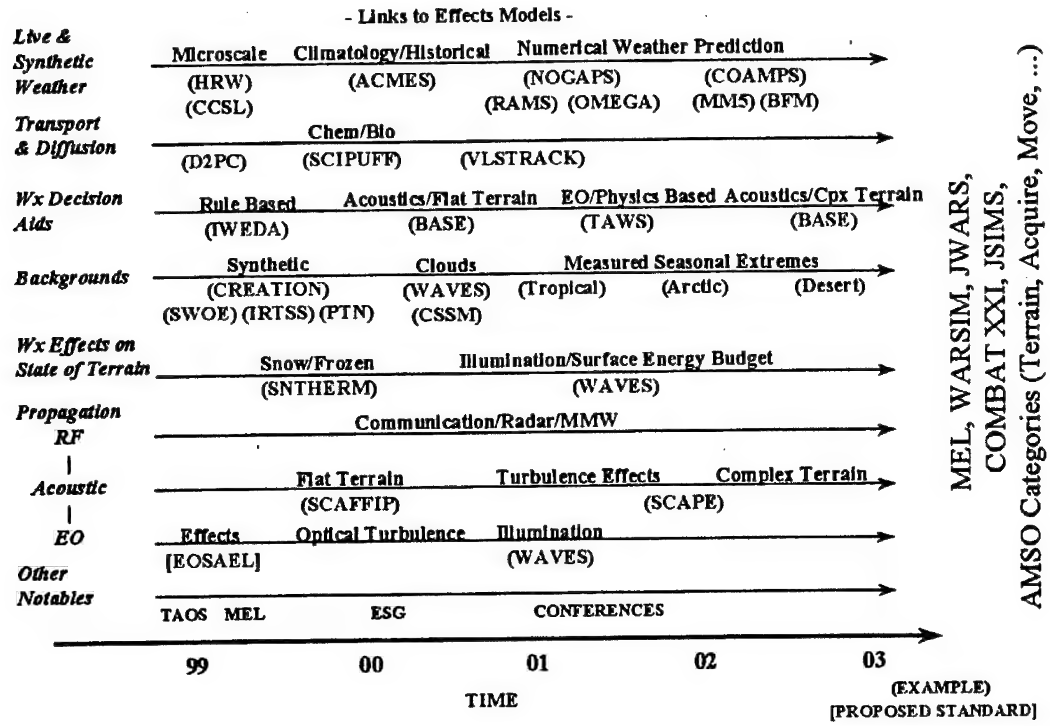

Figure 3. Dynamic atmospheric environments roadmap.

To achieve these objectives the DAE category works to establish standards for use in the U.S. Army M&S environmental community. This is accomplished through the standards development process by applying category requirements. This process allows reuse and prevents duplication of effort; it is influenced by the environmental community (DoD, industry and academia) by using the tools developed (see 2.3) under the overarching guidance of AMSO and by participating in the ongoing discussion within the DAE category.

Modeling efforts leading to the development of standard algorithms in the DAE area are, as might be expected, strong in some areas and in need of additional effort in others. Models that are chosen to lead toward standards must be relevant to Army problems and must also have a degree of maturity as evidenced by verification and validation efforts and also by acceptance and usage within the Army community. EOSAEL contains such models. EOSAEL was developed initially in 1979 by the U.S. Army Atmospheric Sciences Laboratory, now the ARL Information Science and Technology's Battlefield Environment Division, and currently consists of 22 models. EOSAEL is a comprehensive library of fast-running theoretical, semi-empirical, and empirical computer models that describe various aspects of atmospheric propagation and battlefield environments. The models are

oriented more to engineering than to first-principles. The philosophy was to include models that gave reasonably accurate results with a minimum of computer time for conditions that may be expected on the battlefield. EOSAEL studies have been performed for sensitivity analysis, system performance, countermeasure, and cost operations effectiveness analysis; it has also been used for sensor applications, wargaming and visualization effects. Finally, EOSAEL models and documentation are available to qualified users through the Tri-Service Test and Evaluation Community Network (TECNET), (http://tecnet0.jcte.jcs.mil:9000/), and through the ONTAR Corporation (http://www.eosael.com/). Thus, EOSAEL meets many of the requirements for becoming a standard.

However, many of the models in EOSAEL deal with specific battlefield situations that are relevant only to specialized fields (narrow-beam scattering, obscuration caused by helicopter downwash, etc.). On the other hand, models such as CLIMAT, COMBIC, and XSCALE are extensively used throughout the environmental community. These models have been approved as standards for the DAE category and are briefly discussed here.

- The CLIMAT model provides climatology for selected regions throughout the world and was compiled using the U.S. Air Force Environmental Technical Applications Center's (now the Combat Climatology Center) meteorological database. The CLIMAT is available online through MEL.

- The smoke model, COMBIC, the U.S. Army's de facto smoke model, has had extensive validation performed on it, is resident in many wargames (CASTFOREM, Janus, ModSAF, etc.), and has been used as the basis for many smoke visualization efforts.

- The XSCALE model, which deals with extinction due to natural aerosols, is semiempirical and therefore by its very nature has been validated, has been incorporated into models such as the low resolution transmission Low Resolution Transmission (LOWTRAN) model, is available on-line through MEL, and has been used in the STOW-SE program for visualization purposes.

To allow the reader to have an easily accessible place for obtaining information on these models, an abridged documentation for each model is presented here. This allows the reader to obtain a reasonable understanding of what these models do and the physics or measurements that went into their construction.

4. Standards Models

EOSAEL was designed to be a state-of-the-art computer library that describes various atmospheric effects in battlefield environments. In particular, many of the EOSAEL models deal with transmission of electromagnetic radiation through natural and obscured atmospheres. Transmittance (*T*) is the quantity that defines the fraction of the original energy that is left in a beam after passing along the optical path or line of sight (LOS). Thus *T* is a fraction between 0 and 1 and has no physical units. A transmittance *T* of 0.35 means that 35 percent of the original energy will remain after passing along that particular optical path. Energy is removed from the propagating beam through scattering of the energy out of the LOS and by absorption of energy along the LOS. The combination of both processes is called extinction. Strictly speaking, transmittance is wavelength dependent. However, within the atmosphere small regions, or "bands," exist where the atmospheric extinction is relatively constant as a function of wavelength; these regions are commonly known as atmospheric "windows." It is in these windows that U.S. Army broadband sensors have been designed to operate.

In the COMBIC smoke model formulation the wavelength dependent mass extinction coefficient, α_λ, is employed. α_λ describes the extinction encountered in traversing 1 m of an aerosol cloud which has a concentration of 1 g/m^3. α_λ has units of m^2/g and is different for each type of aerosol.

The transmittance, *T*, is determined by the Beer-Lambert law:

$$T = e^{-\alpha_\lambda \int_0^L C(s)ds} = e^{-\alpha_\lambda CL} \tag{1}$$

where *CL* is the concentration length defined as the integral of the aerosol concentration *C* (g/m^3) over the optical path length *L* (m). *CL* is thus the total mass density integrated over the LOS, in units of g/m^2. The product α_λ *CL* is itself dimensionless and is called the optical depth, or optical thickness of the path through the aerosol.

In the aerosol extinction model (XSCALE), Eq. (1) is formulated in terms of the wavelength dependent extinction coefficient K_λ,

$$T = e^{-K_\lambda L}; \tag{2}$$

Eqs. (1) and (2) are equivalent.

Research grade models and/or field measurements were used to develop the models in EOSAEL. Some of the models were developed in academia, but many were developed as part of the basic research program of ARL. Many of the development efforts were assisted by contractors. All models were adapted to a standard format of input and output. The first version of EOSAEL was released in 1979; additional releases were in 1980, 1982, 1984, 1987, and 1992. These many versions of EOSAEL have incorporated numerous changes in algorithms, reflecting advances in mathematical techniques and/or comparison with field tests. As such, EOSAEL is considered to be a mature library, containing codes suitable as standards in the DAE category.

Three EOSAEL models, CLIMAT, COMBIC, and XSCALE are explored in some detail below. Since extensive user and technical documentation is available for all EOSAEL models, only abridged documentation for the CLIMAT, COMBIC, and XSCALE models are presented here. The reader is referred to the current documentation [12,13,14] for further physics details, input parameters/sample output, a complete set of references, and comparison with other codes and/or measurements (validation and verification). CLIMAT and XSCALE model calculations are also available on-line through MEL.

Currently, EOSAEL models and documentation are distributed to users through TECNET, http://tecnet0.jcte.jcs.mil:9000/. To obtain access to EOSAEL via TECNET, send email to awetmore@arl.mil. In addition, a Windows® version of EOSAEL can be obtained through the ONTAR Corporation; the interested reader is referred to http://www.eosael.com for additional details.

4.1 The Climatology Model CLIMAT

The CLIMAT model is based on conditional statistics or separate statistics for each of several meteorological conditions. [12] Twenty-two meteorological conditions or classes were determined based upon obscuration type, visibility, ceiling height, and absolute humidity. Table 2 lists these classes.

Table 2. Meteorological condition classification used in CLIMAT

Class Description	
1 - Fog, haze, and mist with visibility <1 km.	2 - Fog, haze, and mist with visibility ≥1, <3 km.
3 - Fog, haze, and mist with visibility ≥3, <7 km.	4 - Fog, haze, and mist with visibility ≥ 7 km.
5 - Dust with visibility <3 km.	6 - Dust with visibility ≥ 3 km.
7 - Drizzle, rain, and thunderstorms with visibility <1 km.	8 - Drizzle, rain, & thunderstorms with visibility ≥1, <3 km.
9 - Drizzle, rain, and thunderstorms with visibility ≥3, <7 km.	10 - Drizzle, rain, and thunderstorms with visibility ≥7 km.
11 - Snow with visibility <1 km.	12 - Snow with visibility ≥1, <3 km.
13 - Snow with visibility ≥3, <7 km.	14 - Snow with visibility ≥7 km.
15 - No sensible weather & absolute humidity <10 gm/m^3.	16 - No sensible weather & absolute humidity ≥10 gm/m^3.
17 - Visibility <1 km and ceiling height <300 m.	18 - visibility <3 km and ceiling height <1000 m.
19 - Ceiling height <300 m.	20 - Ceiling height <1000 m.
21 - No ceiling.	22 - All conditions combined.

The CLIMAT classes are not mutually exclusive as an observation could simultaneously report fog, rain, and snow causing it to be counted in each of three classes. The 22 classes should not be combined as though they are independent to make new classes.

For each observation within each class, the meteorological parameters [temperature, dew-point, absolute humidity, relative humidity, visibility, sea-level pressure, wind speed, wind direction, cloud (base) height, cloud cover or amount, and Pasquill stability category] were used to compute climatological statistics (table 3) for four seasons and four time periods during the day for each of the climatological regions. There are 74 separate regions covered by CLIMAT as presented in table 4. These regions have been concatenated and are delineated in black in figure 4.

Table 3. **CLIMAT meteorological parameters and statistics**

Meteorological parameter	Mean	Standard deviation	Percent occurrence
Temperature (°C)	X		
Dew-point (°C)	X		
Absolute humidity (g/cu m)	X		
Relative humidity (%)	X		
Visibility (km)	X		
Sea-level pressure (mbar)	X		
Wind speed (m/s)	X	X	
Wind direction (30° intervals)			X
Cloud height (km)	X		
Cloud cover (%)	X	X	
Pasquill category (A-F)			X

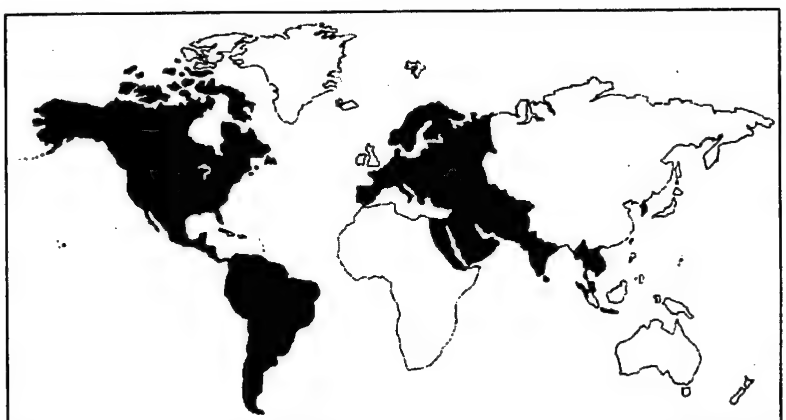

Figure 4. Regions of the world covered by CLIMAT.

Table 4. The 74 climatic regions available in CLIMAT

1. European Lowlands	2. European Rhine Valley
3. European Highlands	4. European Alpine
5. Mideast Deserts	6. Mideast Coastal
7. Mideast Persian Gulf	8. Mideast Red Sea
9. Mideast Eastern Mountains	10. Mideast Indus Valley
11. Korean East Coast	12. South Korea
13. West Korea	14. Alaskan Tundra
15. Alaskan Subarctic Continental	16. Alaskan Southern Coast
17. Western Scandinavia	18. Eastern Scandinavia
19. Central America Pacific Side	20. Central American Interior
21. Central America Atlantic Side	22. Mexico Subtropical
23. Mexico Pacific	24. Mexico Highlands
25. Mexico Tropical	26. South America Tropics
27. South America Desert West	28. South America Desert Central
29. South America Subtropics	30. South America Subpolar
31. South America Highlands	32. India West/Central Region
33. India Northern Valleys	34. India Tropical Area
35. Southeast Asia	36. European Adriatic
37. European Aegean	38. European Balkan Highlands
39. European Balkan Plains	40. European Dinaric Alps
41. European Po Valley	42. European Central Mediterranean
43. European Rhine Valley	44. European French Plateau
45. European NW Mediterranean	46. European Spanish Plateau
47. European Atlantic Coast	48. Western Canada
49. Sacramento Valley	50. Northern Rocky Mountains
51. Central Rocky Mountains	52. Southern Rocky Mountains
53. Southwestern Desert	54. Northern Inter-Mountain
55. Southern Inter-Mountain	56. Canadian Prairie
57. Northern Great Plains	58. Central Great Plains
59. Southern Great Plains	60. Upper Mississippi Valley
61. Middle Mississippi Valley	62. Lower Mississippi Valley
63. Middle Atlantic Coast	64. Southern Atlantic Coast
65. Gulf Coast	66. Southern Pacific Coast
67. Central Pacific Coast	68. Northern Pacific Coast
69. Tennessee Valley	70. Ohio Valley
71. Great Lakes	72. Eastern Great Lakes
73. Northern Atlantic Coast	74. Canadian Atlantic Region

The relative humidity R was computed from the equation

$$R = 100e(D)/e(T) \tag{3}$$

where

T	=	ambient temperature in degrees Kelvin
D	=	dew-point temperature in degrees Kelvin
e(X)	=	vapor pressure in millibars, with X = D or T.

Vapor pressure was obtained from the equation

$$\ln[e(X)/6.105] = 25.22(X - 273)/X - 5.31 \ln(X\text{-}273) \tag{4}$$

and the absolute humidity AH was computed from the equation

$$AH = 216.68e(D)/T. \tag{5}$$

The Pasquill stability category was obtained from a sequential procedure. The procedure starts by calculating the solar angle parameter S. Let A denote the solar angle in degrees above the horizon (negative if below the horizon) and S is determined by the inequalities,

$$\begin{aligned} A \le 0 &\rightarrow S = 0 \\ 0 < A \le 15 &\rightarrow S = 1 \\ 15 < A \le 35 &\rightarrow S = 2 \\ 35 < A \le 60 &\rightarrow S = 3 \\ 60 < A \le 90 &\rightarrow S = 4 \end{aligned}$$

with A computed for the station latitude and longitude and the time of day and Julian date for each observation.

The next step in the procedure calculates the net radiation index NRI. Let C denote the cloud cover in octants or eighths, H denote the cloud base height in hundreds of feet, and NRI $\in$ [1,...,7]. The NRI was determined by the values of C, H, A, and S according to the conditions in table 5.

Table 5. Net radiative index as a function of cloud cover (C), cloud base height (H), and solar angle (A)

C	H	A	NRI
9 - 10	All	All	5
8	<7	All	5
8	≥7	≤0	6
4 - 7	All	≤0	6
0 - 3	All	≤0	7
0 - 4	All	>0	5 - S
5 - 7	<7	>0	7 - S
5 - 8	7 - 16	>0	6 - S
5 - 8	>16	>0	5 - S

The value of C = 9 or 10 denotes an obscured sky. Given C = 8, H >7, and A >0, 1 was added to the NRI obtained above. Next, when A >0 and NRI >4, NRI was set equal to 4. [15] Now if U denotes the wind speed in knots, then the Pasquill stability index may be obtained from table 6 and the value of NRI.

Table 6. The Pasquill Stability Category (A - F) as a function of the wind speed (U) in knots and the net radiative index

	Net radiative index						
	1	2	3	4	5	6	7
$0 \leq U < 2$	A	A	B	C	D	F	F
$2 \leq U < 4$	A	B	B	C	D	F	F
$4 \leq U < 6$	A	B	C	D	D	E	F
$6 \leq U < 7$	B	B	C	D	D	E	F
$7 \leq U < 8$	B	B	C	D	D	D	E
$8 \leq U < 10$	B	C	C	D	D	D	E
$10 \leq U < 11$	C	C	D	D	D	D	E
$11 \leq U < 12$	C	C	D	D	D	D	D
$12 \leq U$	C	D	D	D	D	D	D

A complete climatology model as described in this section is available for each season, for each of the four daily time periods, and for each of the 74 regions. The model contains statistics for any of the 22 meteorological classes listed in table 2.

4.2 The Smoke Model COMBIC

The COMBIC model quantifies the effects of battlefield obscurants on transmission at visible through infrared wavelengths for electro-optical (EO) sensors. [13] The COMBIC computer model predicts spatial and temporal variation in transmission produced by various U.S. Army munitions and vehicles. COMBIC models the effects of reduction in electromagnetic energy by combining the munition characteristics with real world meteorological information. It produces transmission histories at any of seven wavelength bands for a potentially unlimited number of sources and LOS. The term LOS is also used in some combat models to represent a path with a clear view unobstructed by terrain. COMBIC, however, does not determine if terrain intercepts an optical path. This is left to other models. COMBIC includes only the transmission reductions by obscurant aerosols; natural atmospheric gases, haze, rain, etc., are not included in this model.

COMBIC was designed to be computationally fast without losing accuracy for wargame modeling applications. Computations are performed in two phases. First (phase I), a cloud history file, is preprocessed for one or more obscurant source types selected from a menu or defined through user inputs. Except for wind direction, all meteorological influences are included in these phase I calculations of transport, rise, and diffusion of the obscurant clouds. In separate, phase II calculations, COMBIC builds a user-defined scenario of smoke and dust sources. By table lookup and scaling of phase I histories, cloud concentrations at any given time are computed. Path-integrated concentration is determined for each observer-target pair (LOS), and transmittances are computed at each of seven wavelength bands for (in principle) any scenario which is defined by multiple sources and active LOS. Phase II emphasizes computation speed. Efficient techniques are used to determine the path-integrated cloud concentrations over each LOS. A filtering process ignores clouds that do not contribute to the path integral. Bookkeeping functions add target-observer pairs, as specified, add new sources to the scenario, and remove dissipated clouds. Phase II also uses scaling laws to model moving sources that have different speeds and directions but which share a common cloud history produced by phase I.

COMBIC finds the concentration length (*CL*) value appropriate to a particular region and time, multiplies by the corresponding mass extinction coefficient (α_λ), and then obtains the transmittance using Eq. (1). If the path of a beam passes through a series of different types of aerosol clouds,

the transmittance of each is found and then the transmittances are multiplied to obtain the total transmittance. Equivalently, the optical thickness through each cloud can be determined. These are added together, and the exponential in Eq. (1) is used to evaluate the total transmittance due to the smoke cloud. COMBIC performs these actions so the output quantity is the combined transmittance through all clouds present in the path.

4.2.1 Cloud Descriptions and Path Integration Methods

COMBIC describes obscurant clouds as combinations of subclouds. Each subcloud is defined as either a single Gaussian puff or as a continuous Gaussian plume. COMBIC further distinguishes subclouds as buoyant or nonbuoyant, depending upon whether heat is released into the cloud during the formation process. A Gaussian puff is an ellipsoidal volume with concentration which is greatest at its center (x_c, y_c, z_c) and which decreases with distance according to scaling lengths (σ_x, σ_y, σ_z). The concentration at any point, (x, y, z) relative to a Gaussian puff centered on (x_c, y_c, z_c) and containing a total mass of obscurant M, is then

$$C(x,y,z) = \frac{M}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} e^{-\frac{1}{2}\left[\left(\frac{x-x_c}{\sigma_x}\right)^2+\left(\frac{y-y_c}{\sigma_y}\right)^2+\left(\frac{z-z_c}{\sigma_z}\right)^2\right]}. \tag{6}$$

In general, COMBIC allows for a scavenging coefficient, δ, for the removal of mass by deposition or evaporation. Evaporation of volatiles can still result in some long-term, non-volatile component, f_d, of the original mass, however. Then M becomes time dependent:

$$M(t) = M\,[\,f_d + (1 - f_d)e^{-\delta t}]. \tag{7}$$

The continuous Gaussian plume is described by a similar concentration equation:

$$C(x_c;y,z) = \frac{\dot{m}}{2\pi\mu\sigma_y\sigma_z} e^{-\frac{1}{2}\left[\left(\frac{y-y_c}{\sigma_y}\right)^2+\left(\frac{z-z_c}{\sigma_z}\right)^2\right]}, \tag{8}$$

where

μ = wind speed

$\dot{m}$ = time rate of obscurant production which applies at the location (x_c, y_c, z_c).

Although it appears as simple as the concentration equation for the Gaussian puff, the concentration of the Gaussian plume is complicated by the fact that the variables depend on the downwind distance x_C from the source as well as on time. Figure 5 shows the relevant geometry of the plume parameters. In principle, the cloud history would, therefore, require a two-dimensional, space-time array of (y_C, z_C, σ_y, σ_Z, $\dot{m}$ μ, δ) values for an appropriate two parameter table of x_C and t values. However, with the aid of simplifying assumptions, these potentially huge tables can be reduced considerably in size.

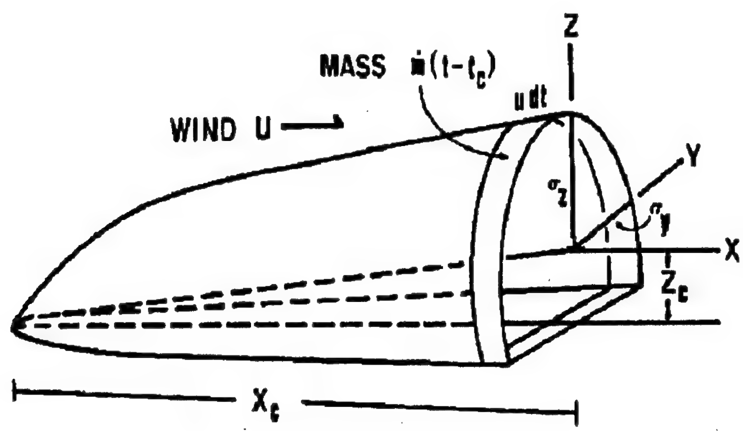

Figure 5. Parameters that describe a Gaussian plume.

4.2.2 The Diffusion Model

Ambient turbulence in the atmosphere causes a decrease in obscurant concentration as the puff or plume diffuses (expands) downwind. The effect of diffusion in COMBIC is contained in the parameters σ_X, σ_Y and σ_Z. These are directly related to cloud dimensions.

The values of the sigma's for puffs, in relation to the downwind travel distance from the source $\bar{x}$, is dependent on the Fractional Stability Category, wind speed, scaling ratio, and surface roughness length for downwind distance greater than the distance associated with a downwind

travel time of 30 s. For instantaneous Gaussian puffs, the equation for finding the longitudinal dispersion length is,

$$\sigma_{x_l} = \left[\sigma_{x_o}^2 + \sigma_{x_s}^2 + \sigma_{x_t}^2\right]^{\frac{1}{2}}, \tag{9}$$

where

σ_{x_o} = initial expansion or "source sigma"

σ_{x_s} and σ_{x_t} = vertical wind shear influences and longitudinal diffusivity of a puff, respectively, and are determined by:

$$\sigma_{x_s} = \frac{0.012}{\sigma_z}\left\{\left[\frac{x}{\ln .53\frac{\sigma_z}{\sigma_o} + \Psi_M\left(\frac{z}{L}\right)}\right]^3 \frac{\Phi_M^2}{\Phi_H}\right\}^{\frac{1}{2}}, \tag{10}$$

$$\sigma_{x_t} = \frac{3}{\mu}\left[\ln .53\frac{\sigma_z}{\sigma_o} + \Psi\left(\frac{z}{L}\right)\right]^{-2} x, \tag{11}$$

where

Φ_M = dimensionless wind shear
Φ_H = dimensionless lapse rate
Ψ_m = diabatic influence function for momentum
L = Obukhov scaling length

The lateral dispersion length σ_y is considered to be time dependent, highly sensitive to sampling and averaging times, and responsive to changes in surface roughness length, and is represented as

$$\sigma_y = \left[\frac{z_o}{10000}\right]^{\frac{1}{3}}\left[\frac{t}{0.1}\right]\sigma_\theta f_1(x)\,x \tag{12}$$

where

σ_θ = a function of Pasquill Stability Categories
z_o = surface roughness length, in meters, and can be determined from tables in [13]

$$\sigma_\theta = 9.714 - 4.925P + 0.402P^2 + 0.118P^3. \tag{13}$$

The procedure used to determine Pasquill category is documented fully elsewhere [15].

The function $f_1(x)$ is given by

$$f_1(x) = \left[1 + 0.0308x^{0.4548}\right]^{-1}, \tag{14}$$

for along wind distance of 10^4 m or less. For distances greater then 10^4 m,

$$f_1(x) = 33x^{-\frac{1}{2}}, \tag{15}$$

The vertical dispersion length is found to be independent of along wind travel time, but is dependent upon the surface roughness length and is represented by:

$$\sigma_z = \left[\frac{z_o}{0.1}\right]^{\frac{1}{3}} \sigma_\phi f_2(x) x, \tag{16}$$

where σ_ϕ = function of Pasquill Stability Categories,

$$\sigma_\phi = 5.048 - 1.996P + 0.060P^2 + 0.056P^3, \text{ and} \tag{17}$$

$f_2(x)$ for downwind distances of 5 x 10^3 m or less is,

$$f_2(x) = \left[1 + 0.0422x^{.4548}\right]^{-1}, \tag{18}$$

and for distances greater than 5000 m

$$f_2(x) = 0.33\left[\frac{5000}{x}\right]^{\frac{1}{2}}. \tag{19}$$

Reliable estimates for concentration for a relatively diffusing plume can be found by considering the trivariate (x,y,z) diffusion of a Gaussian puff. Multiple puffs may be then advected or transported along the mean wind direction to represent the plume. The resultant dispersion of gases and aerosols will, of necessity, be less than those simulated or observed for a continuous diffusion situation. The key to successfully modeling expanding clusters of puffs may be found in correctly postulating the form of the longitudinal dispersion of a puff. For continuous Gaussian plumes, the equations are slightly different.

4.2.3 Buoyant Rise

The rise and stabilization of warm obscurant clouds due to buoyancy (that is, the difference in air density or temperature inside and outside the clouds) are very much influenced by the local temperature gradient and turbulent diffusivity of the atmosphere. A warm volume of air, whether natural or due to an exothermic obscurant source, will rise and expand through entrainment of ambient air. Entrainment and mixing cools the volume and makes it denser. If the volume eventually comes to equilibrium with surrounding air, it will cease to rise, perhaps overshooting the equilibrium point at first. This phenomenon is particularly true at night when the earth has cooled by radiation to a temperature below that of the air above it and the sensible heat flux from the surface is negative (downward).

Increasing ambient air temperature with height increases the stability and produces an eventual equilibrium of a rising warm volume. The reverse is true during daylight hours when the sensible heat flux becomes positive (upward). A volume of ambient air raised somewhat into cooler surrounding air will acquire buoyancy, thus promoting a further rise, and hence the conditions are termed unstable. The atmosphere is not a quiescent fluid, however. Unstable conditions and low wind speeds produce warm rising columns of air near the surface. Cooler air convects to replace it. Increasing wind speed also promotes mixing (mechanical turbulence) which tends to drive the atmosphere to more neutral conditions. This turbulence produces a local eddy diffusivity that will tend to break up and halt the rise of slightly buoyant volumes. Buoyant rise is described through a set of three differential equations and several constitutive relations. COMBIC solves the differential equations directly. Much of this work parallels and was heavily influenced by the work of Weil which compared similar differential equations to the approximate buoyancy solutions. [16] Weil compared plume rise from diesel fires with the

database on stack effluents and found good model agreement. He also performed limited analysis of data from high explosive dust tests.

4.2.4 The Boundary Layer Model

COMBIC requires the user to input a set of meteorological parameters at a single reference height (default 10 m). The boundary layer model then produces vertical temperature, density, and wind speed profiles that are physically consistent with the user inputs and that are necessary for transport, diffusion, and buoyancy calculations.

4.2.5 The Smoke Model

The smoke types modeled in COMBIC are presented in table 7.

Table 7. Smoke types modeled in COMBIC

Bulk white phosphorus (WP)
WP wedges, wicks and plasticized WP
Red phosphorus
Hexachloroethane
Fog oil
Winterized fog oil
Diesel fuel smoke
Polyethylene glycol
IR screener
Diesel fuel
Motor oil
Rubber fire mixtures

Users can also potentially specify other smokes. Anthracene, chlorosulfonic acid, brass, graphite, kaolin and titanium tetrachloride smoke extinction coefficients are provided in the code, although none of the menu-specified sources in the model use these compounds as their defaults. Any cloud can also be specified as a moving source (for example, vehicle-generated smoke). Simplified treatment of many sources ignited within an extended area over an extended time period is provided as an option for simulating barrages. The barrage option greatly reduces computation time at the expense of cloud detail. As a continuous source, the barrage may also be specified to be a moving source of obscurant. Moving sources are,

however, restricted to straight-line motion at constant speed.. With suitable ingenuity, the user can simulate a change in direction by "turning off" a moving source at some point along its path and initiating a new source at that time and location moving with a different speed or direction. Scaling laws are provided to transform a basic cloud history computed in phase I (for example, 40 gal per hour diesel oil generation) into the appropriate clouds produced by one or more moving generators having completely different speeds and directions in phase II calculations. Phase II also allows scaling of source strength and thus the same history can be used for a range of obscurant production, for example, rescaling 40 gal per hour fog oil to 20 gal per hour production rate.

4.2.6 High-Explosive and Vehicular-Generated Dust

High Explosive (HE) and vehicular-produced dust obscuration are fundamentally more difficult to model than smoke due to the variations in the natural sources. COMBIC models HE dust generated by static uncased, static cased, and live-fire munitions detonated at any depth or height of burst and for any angle of impact, that is, munition orientation. A model is provided to extend the crater volume prediction to include any user-defined munition and to treat various soil types. A sod depth correction has been added to reduce the computed volume of ejecta from the crater and the amount of dust accordingly. COMBIC approaches the problem of the broad range of sizes of dust particles by dividing the model into clouds of three size ranges. A very large particle "mode" has been added that accounts for the ballistic soil and large agglomerates that remain airborne for only a few seconds. This change was required to better model the effects on millimeter wavelengths. A large particle mode component is included to partly address the dust size distribution from 20 μm to 200 μm, which falls out somewhat more slowly than the very large mode. Finally, a small size "persistent" mode that remains suspended for long periods and contributes the most extinction per unit mass is included.

A submunition option allows the approximate treatment of explosive subunits that form separate craters. The barrage option treats large numbers of munitions impacting over a small area and relatively continuous time interval as a simplified continuous source of dust. The vehicular dust option models the movement of the source and provide scaling relationships for the amount of dust as a function of vehicle speed, weight, and silt content.

HE-generated dust clouds are treated as five subcloud components: (1) a buoyant small particle puff, (2) a buoyant, large particle stem that settles out

with time, (3) a nonbuoyant puff to model the small particle dust skirt, (4) a connecting small particle stem between the skirt and the buoyant clouds and (5) a very-large particle puff that follows a ballistic trajectory. Carbon particulates produced during the detonation process are partitioned among the buoyant clouds and stem.

4.3 The Atmospheric Transmission Model XSCALE

Weather has a profound effect on the performance of all electro-optical devices that depend on the propagation of electromagnetic energy through the atmosphere. The XSCALE model [14] determines the transmittance through naturally occurring aerosols (haze, fog, and ice fog), rain, and snow, for both individual wavelengths and broadband averages in the ranges 0.2 μm to 12.5 μm for LOS paths within 2 km of the Earth's surface. The extinction coefficient K_λ is found either empirically or through Mie theory. The model for haze is based on an application of Mie theory to a theoretical particle size distribution [17] for horizontal paths and an empirical vertical scaling algorithm for slant paths based on the Meppen test results. [18,19,20,21,22] The algorithms used for fog, rain, and snow are based on empirical and semi-empirical models. The aerosols are assumed to be horizontally homogeneous. Equation (2) is used to calculate the horizontal transmittance.

4.3.1 Attenuation along Horizontal Lines of Sight

4.3.1.1 Hazes

An air mass containing particles from the Earth's surface is referred to as haze. The particles become part of the air mass either by the action of surface winds in the cases of rural and maritime air masses; or by human activity in the case of an urban air mass. The three different air masses available in XSCALE are distinguished mathematically by representative particle size distributions at varying relative humidities.

The rural aerosol is a continental-type air mass composed of 70 percent water-soluble substances and 30 percent dust-like particles. The urban aerosol is the rural aerosol with the addition of soot and combustion products. The urban particle size distribution is thus a combination of the rural distribution plus carbonaceous particles in a ratio of 4 to 1. The maritime aerosol is the rural distribution without large particles and with

1 percent given over to a sea-salt distribution. While the sea-salt fraction does depend on location and weather, the 1 percent value was chosen as typical.

Shettle and Fenn's theoretical models [17] of the aerosols of the lower atmosphere are used to calculate extinction and absorption coefficients for the rural, urban, and maritime hazes. This model assumes a bimodal, lognormal particle size distribution of the form:

$$n(r) = \frac{dN(r)}{dr} = \sum_{i=1}^{2} \frac{N_i}{\ln 10 r \sigma_i \sqrt{2\pi}} e^{-\left[\frac{(\log r - \log r_i)^2}{2\sigma_i}\right]}, \tag{20}$$

where

$N(r)$ = cumulative number density of particles of radius r
σ_i = standard deviation for mode i
r_i N_i = the mode radius and the number density associated with r_i.

The particle size distribution is a function of the locale where the air mass was formed and the relative humidity. Mie theory has been used to calculate extinction and absorption coefficients for each haze at eight relative humidities (0, 50, 70, 80, 90, 95, 98, and 99 percent) and at 31 wavelengths (in the range 0.2 μm - 12.5 μm) for each humidity. These results are normalized, at each humidity, to the 0.55 μm extinction and included as a table in XSCALE.

XSCALE uses the empirical Koschmieder relation:

$$K_{\lambda=0.55} = \frac{3.912}{V} \tag{21}$$

to determine $K_{\lambda=0.55}$ from V, where V is the meteorological range, or visibility, and 3.912 corresponds to a 2 percent contrast threshold. XSCALE uses input values for relative humidity, visibility, and wavelength to scale the visible extinction to the IR extinction.

4.3.1.2 *Fogs*

The two models used for fog types are the same ones used in LOWTRAN 7. The two models represent typical advection and radiation fogs. Fog particle size distributions are characteristic of more situations than their labels imply. Consequently, the labels will be dropped, and the particle size distributions will be identified as fog-one and fog-two.

The fog models are implemented in the same manner as the haze models. The extinction and absorption coefficients have been computed, normalized to the extinction at 0.55 μm, and tabulated for the 31 wavelengths (only 100 percent humidity is considered). XSCALE then interpolates between these values for the extinction at the requested wavelength.

4.3.1.3 *Desert Aerosols*

This model arises from measurements taken in North Africa and the southwest United States between 1977 and 1985. Several measurement efforts were examined. The measurements include size distributions, composition, radiation, and total mass loading. As implemented within XSCALE the desert air mass is composed of three components, each component has a different lognormal particle size distribution and indices of refraction. The components represent carbonaceous particles, water-soluble particles, and sand. Two types of sand contribute to the sand component, 50 percent of the sand particles are pure quartz and 50 percent are quartz contaminated with 10 percent hematite. The amount of carbonaceous and water-soluble particles are constant (once they are scaled by the visibility); the sand component increases with wind speed. This model does not consider a humidity dependence. The densities of the components are arbitrary, but are roughly similar to those measured before.

Again, the dust model is implemented in the same manner as the haze model, that is, a lookup table is contained within the XSCALE module. Relative extinction and absorption coefficients have been normalized to the extinction at 0.55 μm are tabulated at 31 wavelengths and four wind speeds. XSCALE performs linear interpolation to determine the relative extinction, absorption, and scattering coefficients at any specific wavelength and wind speed; these are scaled by the visibility. For a constant background air mass, the mass loading increases with wind speed.

4.3.1.4 Rain

The attenuation in the visible and IR range caused by raindrops is calculated in XSCALE by means of Mie theory. The attenuation can be expressed as a function of rain rate. Visible and IR wavelengths are significantly shorter than the radii of most raindrops, which typically vary from 50 μm to a few millimeters. Thus, the XSCALE model assumes a value of 2.0 for the Mie extinction coefficient. This removes the wavelength dependence of the extinction coefficient in this band of the electromagnetic spectrum, resulting in an extinction coefficient of:

$$K = 2\pi \int n(r) r^2 dr \tag{22}$$

where n(r) = rain particle size distribution.

Several different models for raindrop size distributions are found in the literature. The most widely used description is that of Marshall and Palmer [23] which is based on the observations of Laws and Parsons [24]. This distribution is given by the following:

$$n(r) = N_o e^{-8.2R^{-0.21} r} \tag{23}$$

where

N_o = 8×10^3 (m^{-3} mm^{-1})
r = droplet radius (mm)
R = rain rate (mm/h).

With this distribution the extinction coefficient in km^{-1} can be expressed as a function of rain rate:

$$K = 0.365 R^{0.63}. \tag{24}$$

Waldvogel [25] has shown that different size distributions are typical of different rain situations. Joss and Waldvogel [26] developed size distributions for drizzle, widespread rain, and thunderstorm situations. For these three models the extinction coefficient is related to rain rate by the following:

$$K = 0.5089R^{0.63}\text{, drizzle} \tag{25}$$

$$K = 0.3201R^{0.63}\text{, widespread rain} \tag{26}$$

$$K = 0.1635R^{0.63}\text{, thunderstorm} \tag{27}$$

4.3.1.5 *Falling Snow*

Falling snow is defined in XSCALE as precipitating snow carried by a wind of less than 5 m/s and a relative humidity of less than 95 percent. Crystals of falling snow are generally large, 100 μm or more, in comparison to visible and IR wavelengths. The geometrical optics approximation is expected to be valid. Therefore, the extinction coefficient is equal to 2.0 and the resulting extinction is wavelength independent. However, field measurements of transmittance usually have exhibited wavelength dependence in falling snow such that the extinction coefficient increases with wavelength in the absence of coexisting fog. This observed spectral dependence is explained for the most part by considering diffraction effects. For the above conditions the forward direction diffraction lobe is very narrow at visible wavelengths, but increases in width with wavelength. Thus, as the wavelength increases, less diffracted energy is directed along the LOS to enter the transmissometer resulting in an increasing extinction coefficient with wavelength.

The extinction coefficient, as a function of wavelength, is calculated using the following:

$$K = \frac{e^{-0.88C(\lambda)} + 1}{e^{-0.88C(0.55\mu m)} + 1} \frac{3.912}{V}, \tag{28}$$

where C, calculated within XSCALE, is wavelength dependant and is a function of path length, detector radius, and snow particle size.

4.3.1.6 *Blowing Snow*

Blowing snow is defined for XSCALE as snow carried by a wind of speed greater than 5 m/s and a relative humidity less than 95 percent. The spectral dependence of extinction in blowing snow and the relationship between

visibility and the extinction coefficient are determined by Eq. (28). The particle sizes of blowing snow are generally smaller than for falling snow and a value of 100 μm or less for snow particle size is appropriate.

4.3.1.7 *Snow and Fog*

XSCALE defines snow and fog to be falling snow occurring with a relative humidity greater than 95 percent; no height variation is considered. The total extinction coefficient K in the combination of snow and fog is equal to the sum of the extinction coefficient for fog alone plus that of snow alone.

4.3.1.8 *Ice Fog*

Ice fog forms when hot combustion by-products, such as automobile exhaust or artillery gunfire gases, enter a cold air mass of temperature less than -30 C. Rapid cooling produces a supersaturated mixture from which water droplets condense, freeze into ice fog particles, and grow until the vapor is exhausted. Because combustion is a good source of vapor and nucleating material, ice fog is common in populated arctic and subarctic areas. Ice fog also forms over open water, such as cooling ponds and hot springs, although the process is slower and fewer particles result. Attenuation through ice fog has been calculated using Mie theory.

4.3.2 Attenuation along Inclined Lines of Sight

Traditionally, visibility has referred to visual estimates of the range within which certain objects were discernible against the horizon or background. The emphasis has been upon the horizontal visibility.

In low visibility situations, due to either haze or fog, large numbers of observations have shown that the measured visibility at the surface is not representative of conditions a few hundreds of meters, or even tens of meters, above the surface. Therefore, slant path visibility can be significantly different from horizontal visibility. In a significant fraction of the cases, the visibility becomes worse as the height above the surface increases. The extinction and absorption used for hazes and fogs along with semi-empirical formulae for visible extinction and relative humidity profiles are used to predict the IR extinction as a function of height. Extinction within a low lying stratus cloud is modeled by the fog-one particle size distribution.

The transmittance over a path of varying extinction is obtained by using the average extinction along the path in Eq. (2). The average extinction is the path integral of the extinction along the path divided by the path length:

$$\overline{K} = \frac{1}{S}\int_{s_i}^{s_f} K(s)ds\,, \tag{29}$$

where s represents the spatial path, and $S = s_f - s_i$. If z is the vertical displacement of the path ($Z = z_f - z_i$) and θ the elevation angle, then ds can be written as $ds = \frac{dz}{\sin\theta} = \frac{Sdz}{Z}$ ($\sin\theta = Z/S$). Since K depends only on altitude K(s) = K(z). See figure 6 for the geometry.

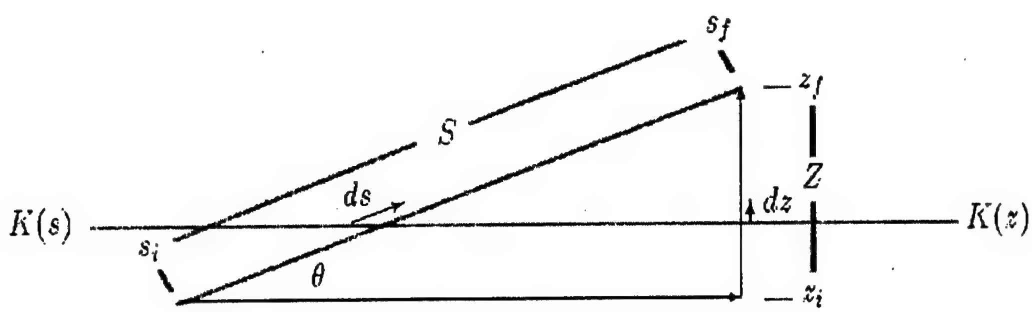

Figure 6. Slant path geometry used in XSCALE.

Thus, K can be rewritten in terms of altitude:

$$K = \frac{1}{S}\frac{S}{Z}\int_{z_i}^{z_f} K(z)dz = \frac{1}{Z}\int_{z_i}^{z_f} K(z)dz. \tag{30}$$

5. Conclusions

Modeling and simulation play an increasingly important role in U.S. Army research, development and acquisition. It is necessary that achievements gained through M&S be preserved and that M&S algorithms be standardized. Failure to do so would be to continuously reinvent the wheel. Standardization leads to cost effectiveness and algorithm reuse. EOSAEL was initially developed in 1979, improved on a routine basis over the years and therefore contains a number of mature codes that deal with various aspects of atmospheric science as applied to U.S. Army battlefield conditions. Three of these codes, CLIMAT, COMBIC and XSCALE have been approved as standards in AMSO's DAE category. In addition, both CLIMAT and XSCALE output is available through MEL. Finally, the COMBIC model is currently embedded in many wargames (e.g., CASTFOREM, Janus) and is the U.S. Army's de facto smoke model.

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Acronyms and Abbreviations

AMSO	U.S. Army Modeling and Simulation Office
ARL	U.S. Army Research Laboratory
ASTARS	U.S. Army Standards Repository System
BED	Battlefield Environment Division
CLIMAT	Climatology
COMBIC	Combined Obscuration Methodology for Battlefield Induced Contaminants
DAE	Dynamic Atmospheric Environments
DoD	U.S. Department of Defense
DUSA (OR)	Deputy Under Secretary of the Army (Operations Research)
EOSAEL	Electro-Optical Systems Atmospheric Effects Library
IWEDA	Integrated Weather Effects Decision Aid
LOS	line of sight
LOWTRAN	Low Resolution Transmission
M&S	Modeling and Simulation
MEL	Master Environmental Library
MODTRAN	Moderate Resolution Transmission
SNAP	Standards Nomination and Approval Process
STOW-SE	Synthetic Theater Of War – Synthetic Environments SWOE Smart Weapons Operability Enhancement

TECNET	Tri-Service Test and Evaluation Community Network
WAVES	Weather and Visualization Effects Simulation
XSCALE	Scaled Extinction model

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